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JILA LIGHT & MATTER

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(*opposite*) Graduate student Shuang "Xavier" Xu aligns a laser in the Weber lab.

Photo Credit: Brad Baxley, JILA

PUFF THE MAGIC ATOMS

The Cornell and Jin groups have just met the challenge of creating and studying an extremely strongly interacting Bose-Einstein condensate (BEC). This feat was reported in *Nature Physics* online in January. An example of an ordinary weakly interacting Bose-Einstein condensate (BEC) is a quantum gas of rubidium atoms (^{85}Rb) all piled up in a little ball whose temperature is a chilly 10 nK. Normally, the interactions between these atoms are weak, and the atoms behave as if they were much smaller than the average distance between nearby atoms, which is typical of a gas. The atoms don't often collide or otherwise interact.

For some time now, physicists have wanted to liven things up in a BEC and investigate what would happen if the ^{85}Rb atoms had stronger interactions. Strongly interacting means the atoms act as if they were puffed up in size until they rub up against, and slide by, one another, just like molecules do in liquid water. In other words, strong interactions would change a quantum gas of ^{85}Rb atoms into a quantum liquid. And, quantum liquids with controllable interactions are a new, fascinating field of study for JILA's atomic physicists.

Until now, however, there had been a major problem with making the atoms effectively puff up and become strongly interacting. Once atoms in the BEC start interacting strongly, they like to form molecules and disappear from the experiment. This disappearing act has made it a challenge to study the behavior of strongly interacting "puffed-up" ^{85}Rb atoms.

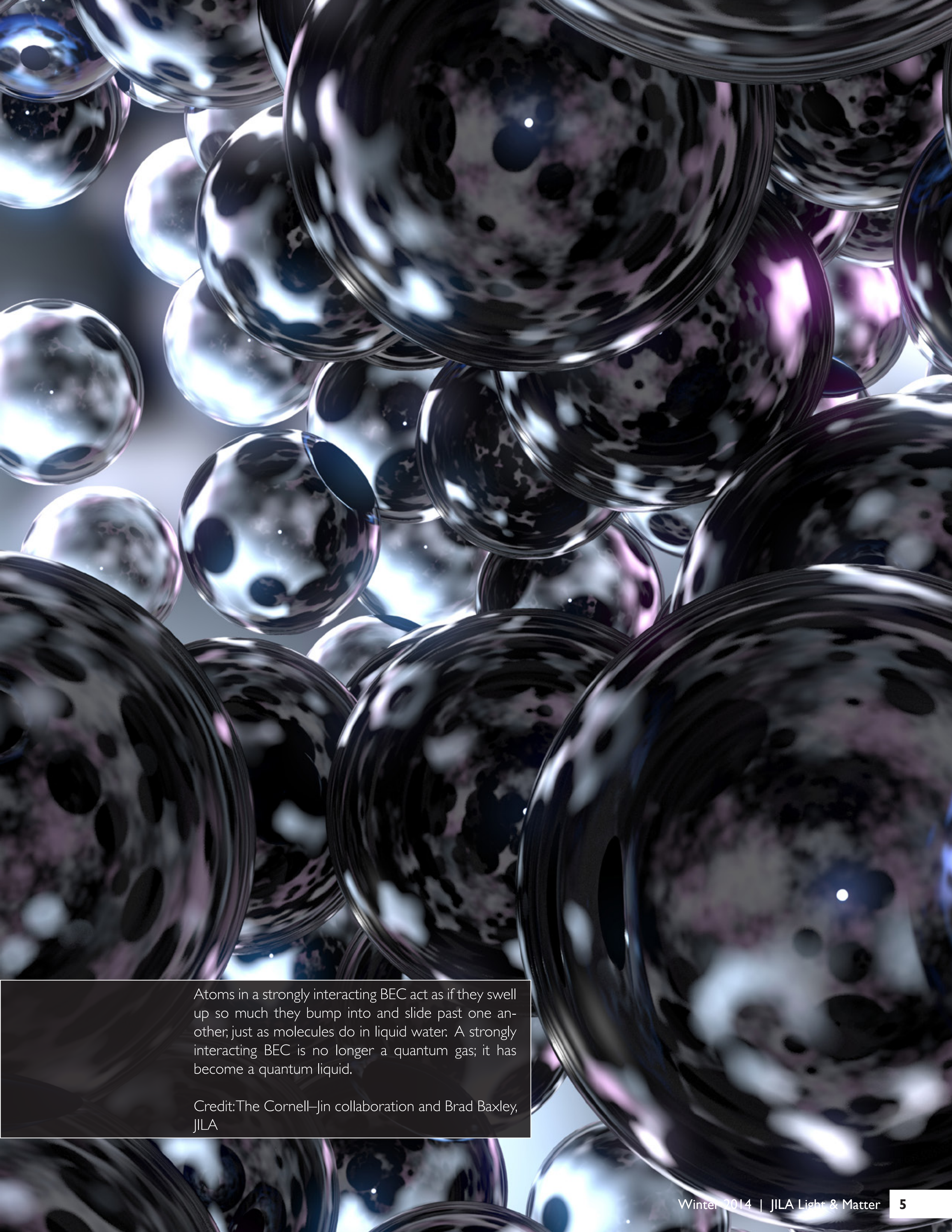
The Cornell-Jin collaboration's secret for making a quantum liquid was the use of a Feshbach resonance to suddenly change the interactions. A Feshbach resonance is a special value of a magnetic field around which small changes in field strength have dramatic effects on the atomic interactions in an ultracold gas. The Feshbach resonance made it possible to rapidly change an ordinary weakly interacting BEC into strongly interacting one.

The rapid part was critical. The researchers were able to make the atoms swell up so fast that there was ample time to study their behavior and atom-atom interactions. Before the atoms formed molecules and disappeared, the researchers were even able to measure and track changes in the velocities of the giant puffy atoms. The scientists responsible for this breakthrough were newly minted Ph.D. Phil Makotyn, graduate student Cathy Klauss, undergraduate student assistant David Goldberger, and Fellows Eric Cornell and Debbie Jin.

The team is already at work figuring out new ways to probe a strongly interacting BEC, including a search for the contact, a property of ultracold ensembles of atoms. The contact was identified by the Cornell-Jin collaboration in a BEC in 2012.

Reference

P. Makotyn, C. E. Klauss, D. L. Goldberger, E. A. Cornell, and D. S. Jin, *Nature Physics* **10**, 116–119 (2014).

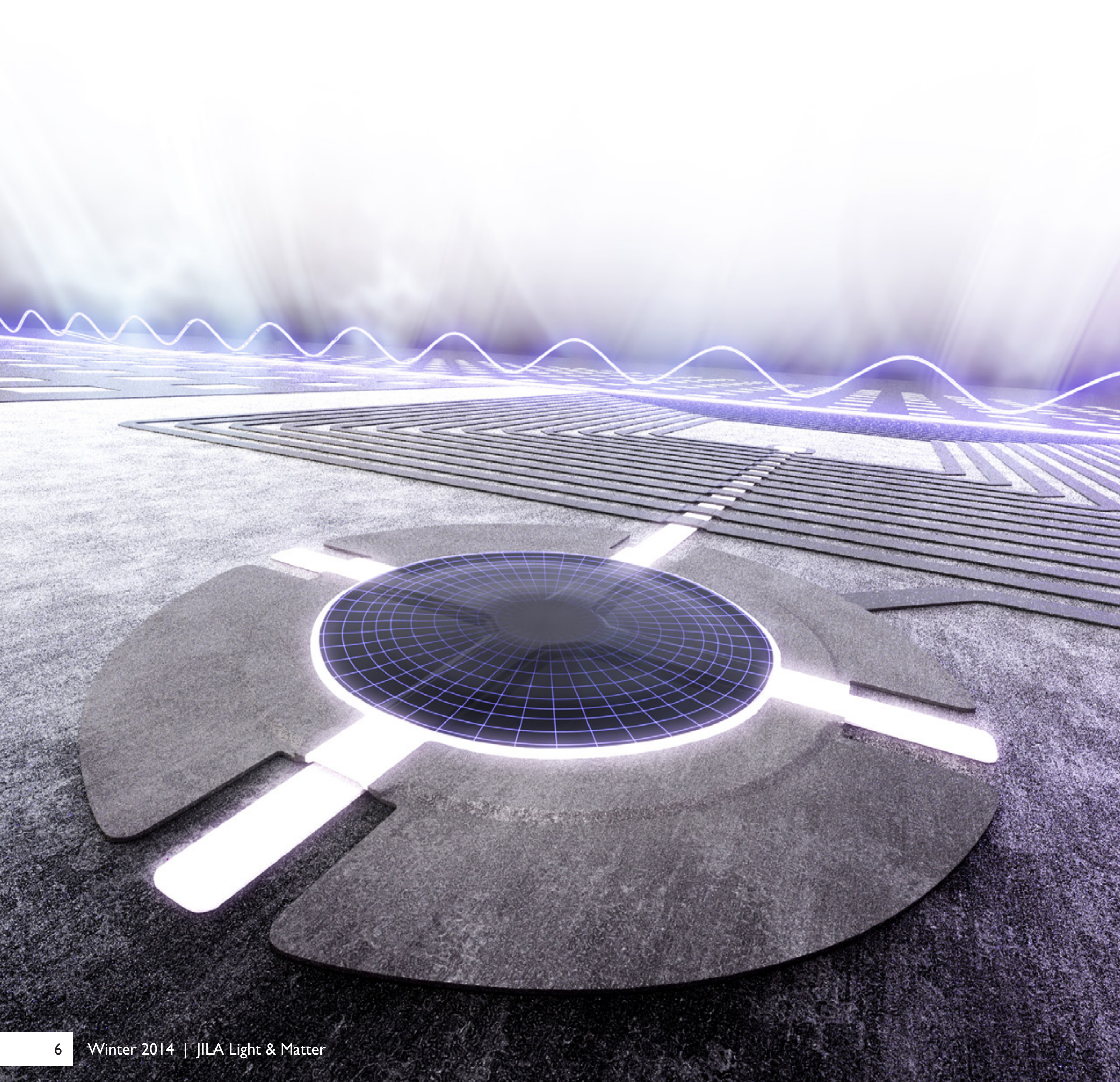


Atoms in a strongly interacting BEC act as if they swell up so much they bump into and slide past one another, just as molecules do in liquid water. A strongly interacting BEC is no longer a quantum gas; it has become a quantum liquid.

Credit: The Cornell–Jin collaboration and Brad Baxley, JILA

Using an electrical circuit (*back*), the Lehnert group has entangled the motion of a drum (*front*) with an electrical signal carried away from the circuit.

Credit: The Lehnert group and Brad Baxley, JILA



THIS IS THE DAWNING OF THE AGE OF ENTANGLEMENT

Tauno Palomaki and his colleagues in the Lehnert group have just gone where no one has gone before: They've entangled the quantum motion of a vibrating drum with the quantum state of a moving electrical pulse. What's more, they figured out how to store half of this novel entangled state in the drum (which is tiny compared to a musical drum, but huge compared to the atoms or molecules normally entangled in a lab). The drum can then generate another electrical pulse that is entangled with the first one! This amazing feat was reported online in *Science* in October 2013.

The Lehnert group's entanglement of a 15-μm-diameter vibrating drum (a mechanical object) with an electrical signal (a.k.a. a microwave field) promises to be a key ingredient in the design of future quantum processors and precision instruments used to detect tiny forces currently too small to sense. It may also be a step along the road to testing the limits of quantum theory itself.

Grasping the importance of this accomplishment requires a basic understanding of quantum entanglement, a strange phenomenon Albert Einstein called "spooky action at a distance." Entanglement means that the quantum states of something physical—such as particles, microwave fields, devices, or voltages—interact and retain a connection, sometimes over very long distances. Once entities are entangled, a measurement of one of them will always be correlated to the measurements of the others—even though the individual measurements appear to be completely random.

"Entanglement means having things tied together by quantum spaghetti," Palomaki says. "Once it happens, things talk to each other in a mysterious way."

One way to think about entanglement is to imagine two blindfolded bar patrons playing darts on opposite sides of the room. Separately, each one misses the bull's eye by an unpredictable amount. But, if the players are entangled, a dart thrown by each one of them will hit the same point on separate dartboards.

Something similar happens in the Lehnert lab, but at temperatures of 15–20 mK. The motion of the cold drum is entangled with the voltage of an electrical signal as it moves away from the drum toward an amplifier. The correlation observed between the drum motion and the signal voltage cannot be described using the mathematics of ordinary, everyday physics. Explaining entanglement requires the peculiar mathematics of quantum mechanics.

All this isn't quite as simple as it sounds. The drum has many possible combinations of position and momentum, and the microwave field has many possible values of amplitude and phase. However, when the researchers measure the microwave field, the measurement itself "forces" the drum into a particular position and momentum. And, once they measure the first pulse, the researchers know for certain what will happen when they measure the second pulse—because the second pulse contains the previous state of the drum. Nevertheless, before any measurements occur, it's impossible to predict what's going to happen!

That said, the new understanding of entanglement between a mechanical object, a microwave field, and signal voltage holds great promise for future research into the nature of the world we inhabit and the invention of some marvelous new devices.

Reference

T. A. Palomaki, J. D. Teufel, R. W. Simmonds, and K. W. Lehnert, *Science* **342**, 710–713 (2013).

(*opposite*) Undergraduate Ian Collett of the Lewandowski group tunes custom electronics in the lab.

Photo credit: Brad Baxley, JILA

PERSISTENCE OF MEMORY

What sets the stage for planet formation? To search for answers to this question, research associate Jake Simon and his colleagues are performing a series of high-level computer simulations of the outer disks around young stars such as TW Hydrae, shown here. Simon's daunting task is being facilitated with new information that has just started to come in from the Atacama Large Millimeter/submillimeter Array (ALMA) observatory in Chile.

ALMA is one of the world's largest ground-based astronomy projects and is sensitive enough to directly image the formation of planets. Information from ALMA and other smaller observatories has already allowed Simon to adjust and enhance his simulation codes to better reflect actual conditions that set the stage for planet formation in disks around young stars. Simon is being assisted in this work by senior research associate Kris Beckwith, Fellow Phil Armitage, and their colleagues from Princeton University and the Harvard-Smithsonian Center for Astrophysics.

"Our work is related to ALMA and the turbulent motions of the gas in the disks," Armitage explains. "ALMA is just coming online and observing these disks with revolutionary sensitivity. We're trying to get our simulations to match what ALMA sees, and we're succeeding."

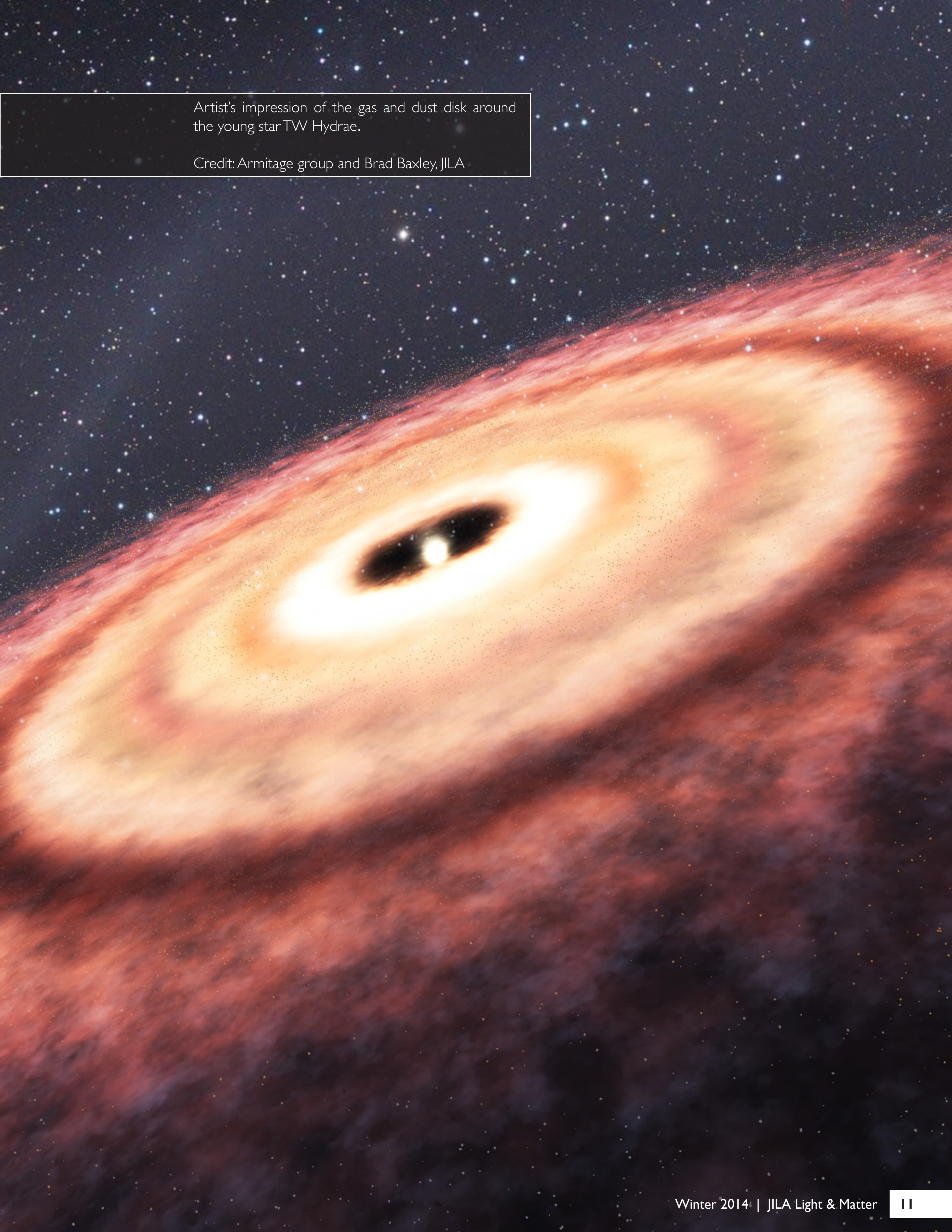
The researchers have known for a long time that most of the gas is found in the outer disk, which corresponds to the location of Neptune and beyond in our Solar System. Because observers can "see" gas spiraling into and colliding with the star (infall), Simon and Armitage want to better understand what is causing this inflow of very low-density gas that mostly consists of hydrogen molecules.

What's tricky about this project is that the researchers have good reason to think that magnetic fields within the gas are key to producing the inflow. However, neutral hydrogen molecules won't be affected by magnetic fields unless they happen to collide with one of the relatively few small-charged particles and free electrons inside the disk.

The researchers are working to simulate turbulence that is strong enough to cause gas in the disk to fall into the star. For this to happen, there must be turbulence all the way through the disk to keep matter spiraling steadily in toward the star.

In their first set of simulations, they discovered that if there's no magnetic field threading the disk, the turbulence is damped enough to suppress infall. In their second set of simulations, they found that even if there is a relatively weak magnetic field (tens to hundreds of micro-Gauss) threaded through the disk, enough turbulence results to account for the ALMA observations.

However, the latest results have left the researchers with a conundrum: Where do the magnetic fields driving inflow from the outer disks come from? Neutral hydrogen molecules don't



Artist's impression of the gas and dust disk around the young star TW Hydrae.

Credit: Armitage group and Brad Baxley, JILA even interact with magnetic fields, and there just aren't very many electrons and ions loose in the disk to create magnetic fields on their own.

The answer they've come up with is that there may be magnetic fields inside the disk left over from the process of star formation. In other words, the memory of how the star itself formed may be important for disk formation and evolution!

References

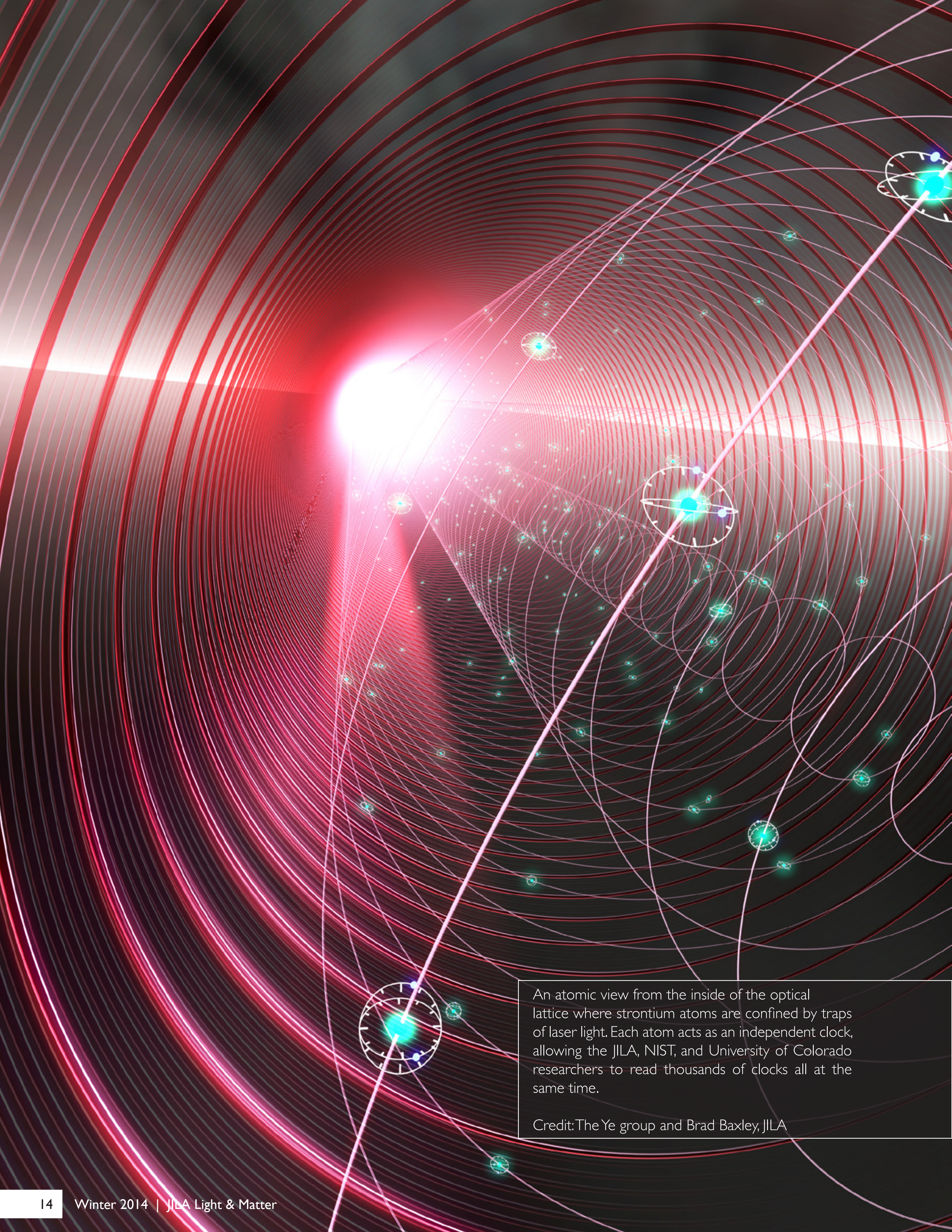
Jacob B. Simon, Xue-Ning Bai, James M. Stone, Philip J. Armitage, and Kris Beckwith, *Astrophysical Journal* **764**, 66 (2013).

Jacob B. Simon, Xue-Ning Bai, Philip J. Armitage, James M. Stone, and Kris Beckwith, *Astrophysical Journal* **775**, 73 (2013).

(*opposite*) The instrument shop's Kels Detra holds a precision part fresh off the CNC mill.

Photo credit: Brad Baxley, JILA


WARNING
KURT



An atomic view from the inside of the optical lattice where strontium atoms are confined by traps of laser light. Each atom acts as an independent clock, allowing the JILA, NIST, and University of Colorado researchers to read thousands of clocks all at the same time.

Credit: The Ye group and Brad Baxley, JILA

A CLOCKWORK BLUE TAKES THE GOLD

JILA and NIST labs are well on the way to creating astonishingly accurate optical atomic clocks based on the neutral atoms strontium (Sr) and ytterbium (Yb). The new technologies are already capable of the most meticulous timekeeping in human history.

JILA Fellow Jun Ye's group has developed an optical atomic clock that uses neutral Sr atoms held in an optical lattice (i.e., crystal of light) to generate the ticks of its clock. The Sr-lattice clock can precisely control the quantum states of more than 1000 atoms simultaneously. In 2012 (as recounted in "The Most Stable Clock in the World," *JL&M*), the group achieved record stability by operating the clock near the limit where quantum noise impacts clock performance. Now, a recent comprehensive evaluation showed that it is more accurate, reproducible, and stable than any other atomic clocks, including those based on single trapped ions. This achievement was reported in *Nature*.

Andrew Ludlow's group at NIST uses Yb atoms to generate ticks for its super stable atomic clock, which shares many characteristics with the JILA Sr-lattice clock, including stabilities basically at the same level. Ludlow, who trained at JILA under Fellow Jun Ye on earlier versions of the Sr-lattice clock, is now working on a comprehensive evaluation of the accuracy, reproducibility, and stability of the NIST Yb-lattice clock. The NIST Yb-lattice clock team also includes Chris Oates, who earned his Ph.D. under Fellow Jan Hall, and other JILA alumni.

The JILA Sr-lattice clock uses laser beams to trap the strontium atoms inside energy peaks and valleys created by light. The result is a clock that is 30 times more accurate and 300 times more stable than the cesium-based atomic clocks currently used as time standards in national laboratories around the world.

The most recent team responsible for developing JILA's high-performing atomic clock includes graduate students Ben Bloom, Travis Nicholson, Sara Campbell, Mike Bishof, and Sarah Bromley; former research associate Jason Williams; research associates Xibo Zhang and Wei Zhang; and Fellow Jun Ye. Many former graduate students and research associates have also contributed to the development of the Sr-lattice clock during the past decade.

The idea of using alkaline earth atoms, such as calcium and Sr, in atomic clocks originated in JILA and NIST in the 1980s and 1990s. In the early 2000s, researchers in Tokyo and JILA realized they could confine Sr atoms in optical lattices without affecting the clock ticks. The lattice largely protects the critical Sr clock transition from being perturbed by outside forces. This advance led to a goal of developing an ultrastable high-accuracy optical atomic clock that would not only work better than existing cesium-based time standards, but also outperform the promising single-ion optical atomic clocks invented in 2001 at NIST.

However, this dream did not come true for more than a decade. Inadequate laser stability prevented scientists from precisely measuring the pure signal produced by many Sr atoms. Now, research in the Ye group has yielded new laser technologies that have brought with them the ability to minimize quantum noise in the Sr-lattice clock.

Clear advantages of the Sr-lattice clock have already emerged. It contains thousands of atoms (as does the Yb clock). The intrinsic quantum fluctuations of these atoms average out during a single measurement of clock ticks; in contrast, ion clocks have only a single ion that flips back and forth between quantum states. It takes a longer time to average down the quantum fluctuations to achieve the same accuracy and reproducibility as the Sr-lattice clock.

The next step in refining the Sr-lattice clock is a study of the internal structure of the Sr atoms, which will allow theorists to more precisely predict clock perturbations due to the blackbody radiation that surrounds all atoms. In the meantime, the Sr-lattice clock is currently the best in the world, according to the recently completed evaluation. In fact, it is so accurate that it is allowing the Ye group to explore the intricacies of the quantum world, which consists of many interacting particles! And if all this isn't exciting enough, the Ye group expects their clock to get even more accurate and stable in the future.

Reference

B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, and J. Ye, *Nature* **506**, 71–75 (2014).

(*opposite*) Fellow Cindy Regal and graduate student Adam Kaufman discussing one of their small drums under a hood in the lab.

Photo credit: Brad Baxley, JILA

bR PHONE HOME

The groups of Fellow Adjoint Markus Raschke and Fellow Tom Perkins joined forces recently to shine light onto a bacterial membrane protein called bacteriorhodopsin (bR). They used a new infrared (IR) light-imaging system with a spatial resolution and chemical sensitivity of just a few bR molecules. In their experiment, the tip of an atomic force microscope (AFM) acted like an antenna for the IR light, focusing it onto the sample. The AFM-tip antenna then helped capture the IR signal emitted by the bR protein and send it back to a detector for identification and location. The AFM-tip antenna works a lot like a cell phone antenna except that it talks to protein molecules.

The protein cell phone is actually an IR nano microscope called s-SNOM (scattering scanning near field optical microscope). The new work has opened up imaging of biological and chemical structures 5000-fold smaller than the diameter of a human hair. In particular, s-SNOM provides a label-free method to probe the chemical composition of a material, easily distinguishing proteins from other chemical constituents such as the fat molecules making up a membrane. Until now, such chemical distinctions were impossible to "see" with ordinary light microscopy and too large and complex to analyze with x-ray crystallography.

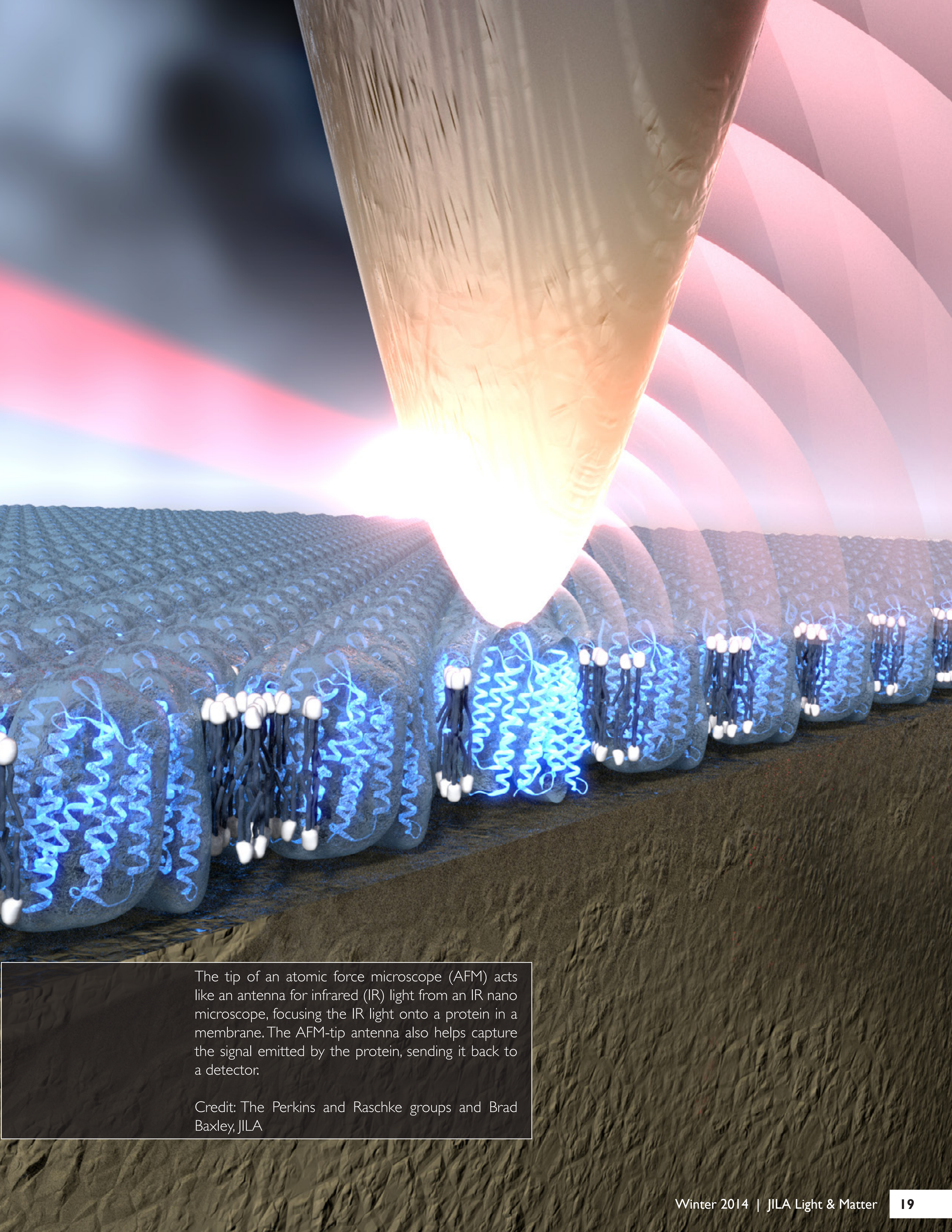
With the new method, the researchers were able to identify the bR protein with a spatial resolution of 20 nm, or the length of 2–3 bR molecules. Plus, the researchers were able to acquire IR spectra of just a handful of protein molecules, compared to about 10,000 molecules required for getting good spectra with a regular IR microscope.

They accomplished this feat by first using a quantum cascade laser to excite amide groups in the protein. Amide groups, which contain carbon, oxygen and nitrogen, vibrate like crazy when excited by IR light. Then, with the help of the ARM-tip antenna in the s-SNOM setup, the researchers tickled the proteins, causing them to reemit the IR light. That made it possible for them to zero in and "see" the bR protein backbones. The researchers responsible for this feat included Raschke, Perkins, research associate Sam Berweger, former undergraduate student assistant Duc Nguyen, research associate Eric Muller, and their colleague Hans Bechtel of Lawrence Berkeley National Laboratory.

The Raschke group is already working on improving the new imaging method with the goal of resolving single molecules, including some in liquid. For its part, the Perkins group plans to continue its quest to better understand membrane proteins, which are the target of 50% of all current and future drugs. The two groups plan to continue their collaboration with the goal of one day being able to probe and understand the structures and functions of the myriad of constituents of living cells. And, they want to do all this in real time and under realistic conditions for life.

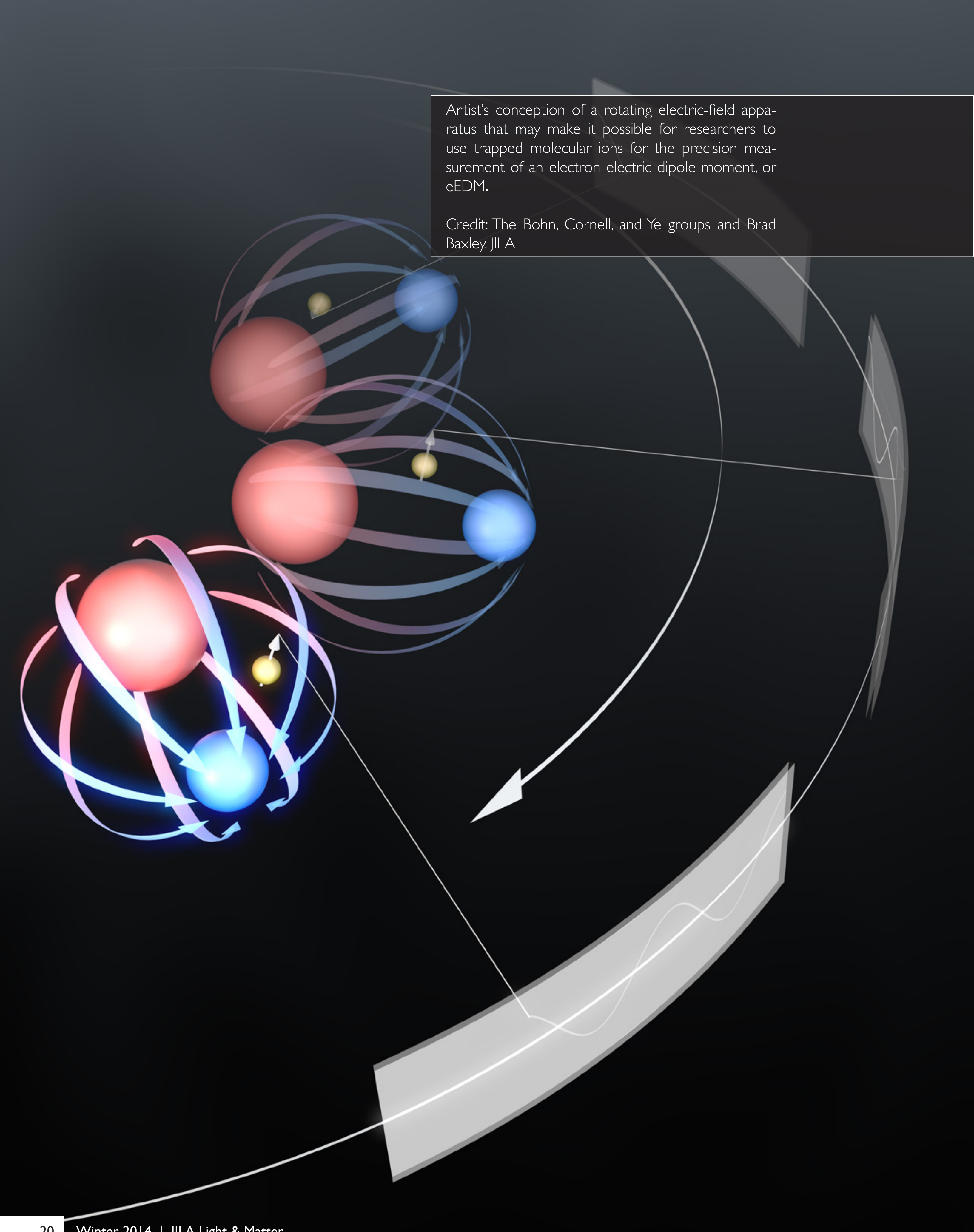
Reference

Samuel Berweger, Duc M. Nguyen, Eric A. Muller, Hans A. Bechtel, Thomas T. Perkins, and Markus B. Raschke, the *Journal of the American Chemical Society* **135**, 18292–18295 (2013).



The tip of an atomic force microscope (AFM) acts like an antenna for infrared (IR) light from an IR nano microscope, focusing the IR light onto a protein in a membrane. The AFM-tip antenna also helps capture the signal emitted by the protein, sending it back to a detector.

Credit: The Perkins and Raschke groups and Brad Baxley, JILA



Artist's conception of a rotating electric-field apparatus that may make it possible for researchers to use trapped molecular ions for the precision measurement of an electron electric dipole moment, or eEDM.

Credit: The Bohn, Cornell, and Ye groups and Brad Baxley, JILA

DIPOLAR EXPRESS

Physicists wonder about some pretty strange things. For instance, one burning question is: How round is the electron? While the simplest picture of the electron is a perfect sphere, it is possible that it is instead shaped like an egg. The egg shape would look a bit like a tiny separation of positive and negative charges. Physicists call this kind of charge separation an electric dipole moment, or EDM. The existence of an EDM in the electron or any other subatomic particle will have a profound impact on our understanding of the fundamental laws of physics.

The Cornell and Ye groups are investigating whether the electron has an EDM—with the goal of either providing an extremely tight upper bound for its value or actually measuring it. They've been working on this problem for nearly a decade because knowing the size of the electron's EDM (eEDM) may help scientists better understand how the world works, including why there's enough matter in the Universe to form galaxies, stars, and planets like our Earth.

Right now, there are several different theoretical models of fundamental particles (such as the electron) and their interactions that attempt to explain how the Universe came to be. Each one predicts a different value for the eEDM. The values range from a charge separation of 10^{-25} to $<10^{-40}$ cm. To put these numbers in perspective, a charge separation of 10^{-25} cm would correspond to an out-of-roundness for a spherical Earth of 2.2 microns (10^{-6} cm), which is roughly the size of a small bacterium. The current published eEDM limit is 10^{-27} cm, which corresponds to an Earth out-of-roundness of .022 microns, or the size of a small virus.

So, if there is an eEDM, it is a pretty darn small one. For starters, an electron with a diameter of $\sim 3 \times 10^{-13}$ cm is whole a lot smaller than the Earth with a diameter of 1,300,000,000 cm. The small size of the electron makes it technically very challenging for researchers to pinpoint and measure the much, much smaller eEDM. Fortunately, the Cornell and Ye groups (with help from the Bohn theory group) have invented a nifty new approach to zeroing in on this important measurement.

The new approach comes compliments of recently minted Ph.D Huanqian Loh, graduate students Kevin Cossel and Matt Grau, former postdoc and graduate student Kang-Kuen Ni (now at Harvard), former graduate student Ed Meyer (now at Kansas State), and Fellows John Bohn, Jun Ye, and Eric Cornell.

The experiment uses a trapped ball of ~1000 ions of hafnium fluoride ions (HfF^+), which Meyer and Bohn originally identified as ideal for an eEDM experiment. Recently, the researchers took the ions and aligned them with an electric field that rotated in time. This procedure caused the axes of all the molecular ions to point in the same direction while still keeping them in the trap. This important step allows the researchers to probe the interaction of an electron inside an ion with large electric fields already present inside the HfF^+ ions.

The idea is that identically aligned electrons in all 1000 ions will help to magnify an eEDM signal (if there is one). And, because the ions can be trapped for a long time, the signal can be measured for much longer than in other experiments in neutral molecules. The new apparatus represents a major advance in the technology for precision measurement of an eEDM.

Cossel and his colleagues are now working on improving their apparatus in anticipation of looking for an eEDM at the level of 10^{-28} or 10^{-29} cm, a level that is predicted by at least one major theory. Measuring at this level tests some of the same physics under study at the Large Hadron Collider in CERN, Switzerland. Never a dull moment!

Reference

H. Loh, K. C. Cossel, M. C. Grau, K.-K. Ni, E. R. Meyer, J. L. Bohn, J. Ye, and E. A. Cornell, *Science* **342**, 1220–1222 (2013).

JILA AT WORK

Across

3. exclusionary Austrian physicist
4. short-lived shower of high-energy radiation
5. dust and gas cloud
7. seventh letter of Greek alphabet
8. fixed-phase waves
10. cation of eEDM search fame
12. changes AC to DC
13. properties differ depending on direction (adj)
14. structure created by intersecting laser beams
16. sulfur-like element attracted to gold
18. parameter that describes a resonator's bandwidth relative to its center frequency
21. having a closed ring of alternate single and double bonds with delocalized electrons
26. element in defined space that is an eigenstate of the particle number operator
28. eight-bit information
31. one weber per square meter
32. change in momentum due to collision
34. gene storage unit
35. half the diameter of a circle
37. hypothetical massive star with a black hole
39. machine for studying quantum behaviors
40. basic structure of all living organisms
41. opposite to direction of biomolecule transcription, translation, synthesis
44. state of a single electron in an atom
49. the hunter
50. the starry branch of physics
51. flight from the law
52. makes bombs and generates electricity
56. when quantum, this effect stops molecules from disappearing
59. Carlo's first name
60. farthest away from ordinary
63. mathemetical description of coordinates and momenta of a particle system
66. this element makes the clock ticks
67. father of molecular astrophysics

Down

1. adjective describing quantized rotational levels associated with vibrational states
2. it's a superconductor below 9°K
3. methods for finding approximate solutions
6. represents points on a Bloch sphere
9. rare earth metal that makes pink salts
11. Herman's resonance
15. heavenly body
16. axial
17. it's a messenger
19. hypothetical subatomic dark-matter particle
20. adjustable resistor that controls current
22. sunscreen 12 miles up
23. condition of a spinning particle
24. models strongly correlated electron systems
25. property of ultracold atom ensembles
27. theory of some nonlinear dynamic systems
29. rapidly rotating neutron star
30. made of rings
33. charged atoms or molecules
36. science of creating electric circuit analogs with cold atoms
38. NH_3
41. short ultraviolet
42. without bend, angle, or curve
43. short for rubidium
45. particles with integral spins
46. closed surface, product of two circles
47. almost every lab in JILA has one
48. unit of electrical resistance
53. equal properties in all directions
54. representation
55. engraving that exposes underlying stone
57. precious metal resembling platinum
58. parasitic one-celled protozoan
61. close to 0˚K
62. theory using simple model to study large complex systems
64. they make up everything
65. nebula in Taurus
66. solitary waves

*** First person to turn in correct puzzle gets REI giftcard! ***

JILA AT WORK


JILA
JILA A·D·1980
AS SEEN BY ZDENEK HERMAN
VISITING FELLOW 1979-80
SAWN
OUT OF ORDER

THE SQUEEZE MACHINE

Research associate Tom Purdy and his colleagues in the Regal group have just built an even better miniature light-powered machine that can now strip away noise from a laser beam. Their secret: a creative workaround of a quantum limit imposed by the Heisenberg Uncertainty Principle. This limit makes it impossible to simultaneously reduce the noise on both the amplitude and phase of light inside interferometers and other high-tech instruments that detect miniscule position changes.

Purdy's team got around this limit by squeezing the quantum state of their laser light. In so doing, the researchers reduced the amount of quantum "noise" in the amplitude, making it possible to use the squeezed laser light to make more precise measurements. However, the noise reduction in the light amplitude came at the cost of increasing the amount of quantum noise in the phase of the laser light. Thus, Purdy didn't violate the laws of quantum mechanics by squeezing laser light.

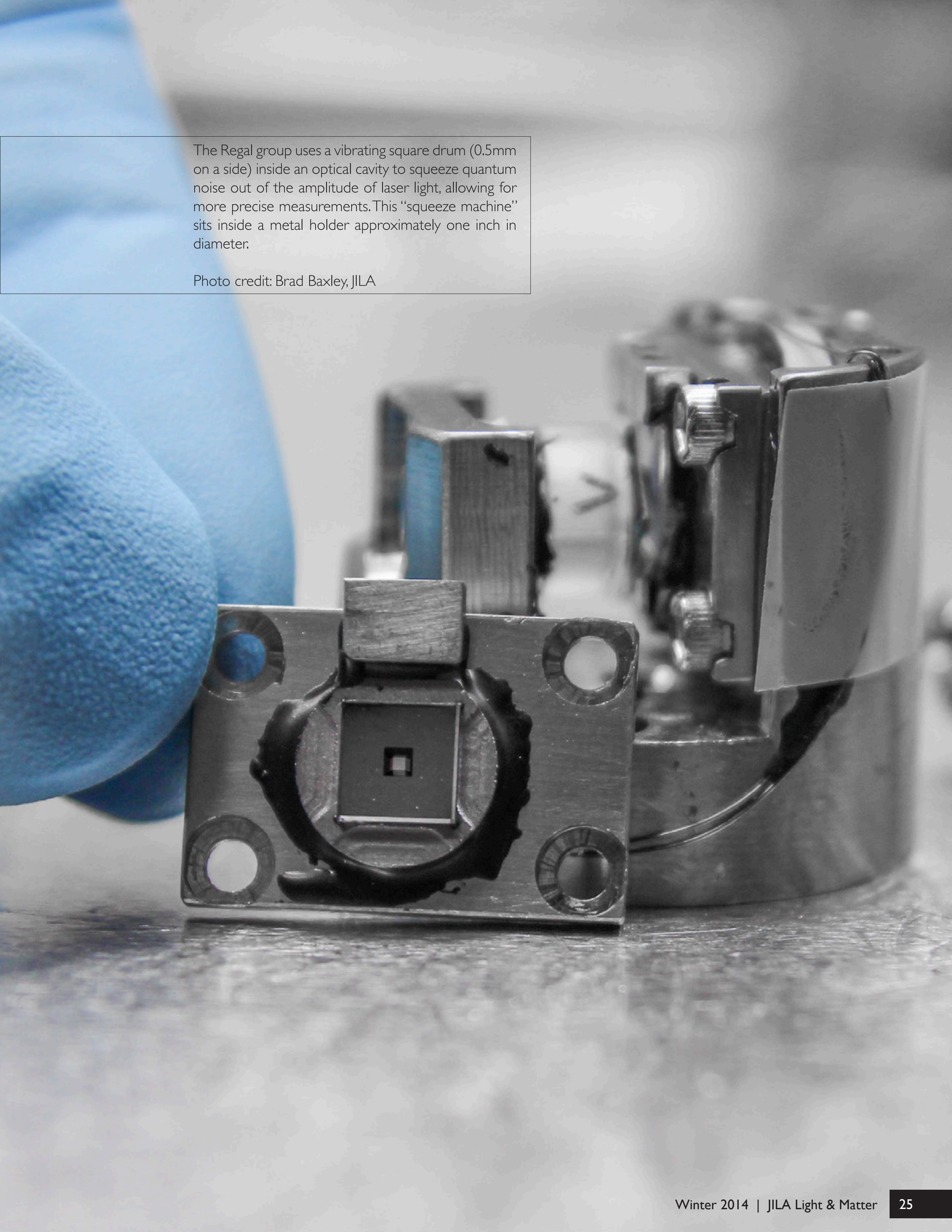
Rather, he and his colleagues built a nifty little squeeze machine that applied these laws. They squeezed the laser light by having it interact with a tiny vibrating drum inside an optical cavity. The use of the drum is a key feature of the new machine because it could provide tailored squeezed light for interferometers for precision measurement.

Here's how the experiment worked: The laser light exerted a force on the drum inside the cavity, causing it to move. This motion caused a shift in the light phase, which linked together the phase and the amplitude of the light field inside the cavity. Taking advantage of this linkage, the researchers were able to arrange for the amplitude of the light to have 32% less quantum noise than it otherwise would have had! As an added bonus, the team was able to show squeezing over different ranges by looking at various combinations of the amplitude and phase noise.

This exciting experiment holds great promise for improving precision measurement in gravitational-wave detectors and in state-of-the-art microscopy.

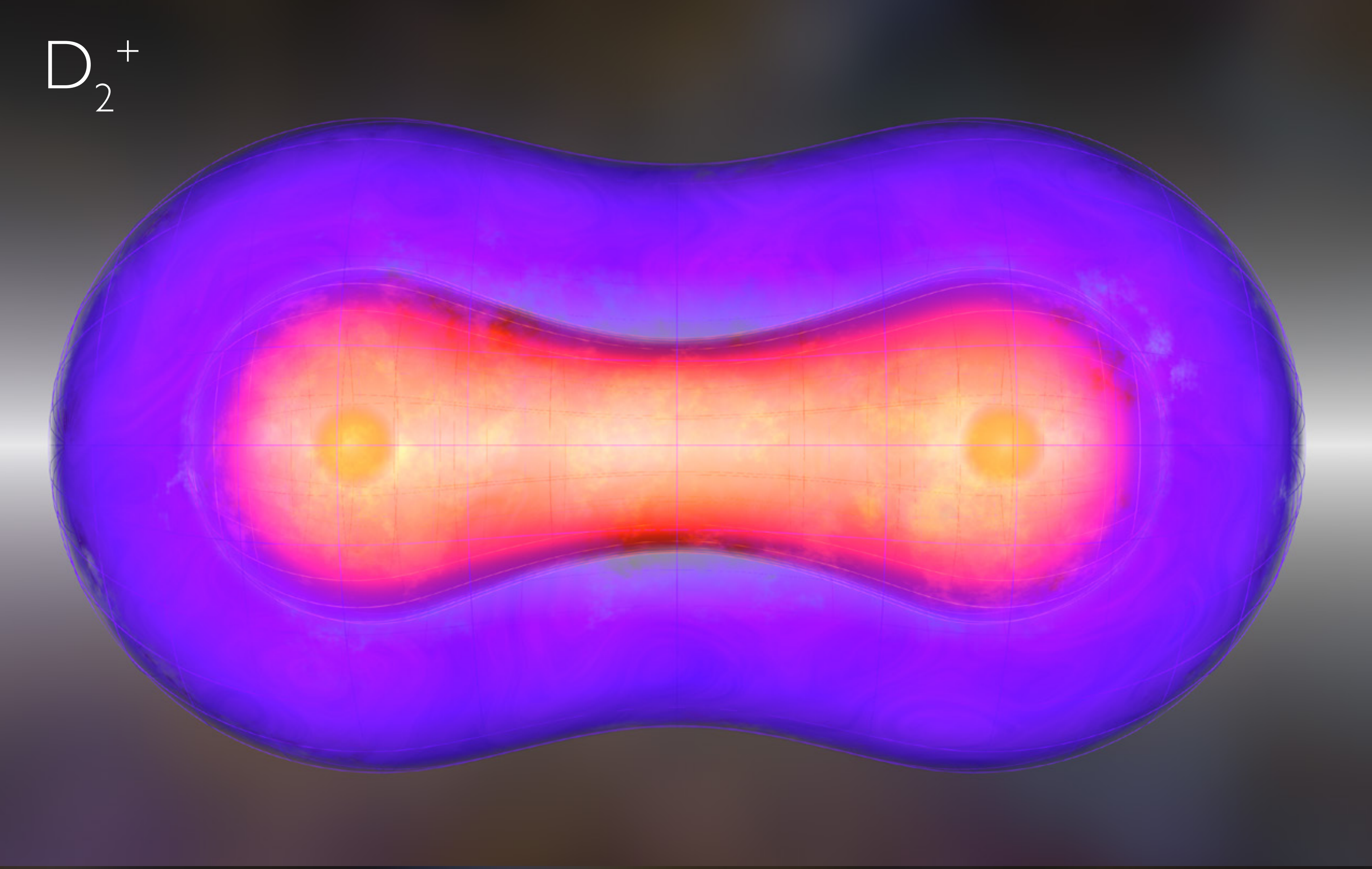
Reference

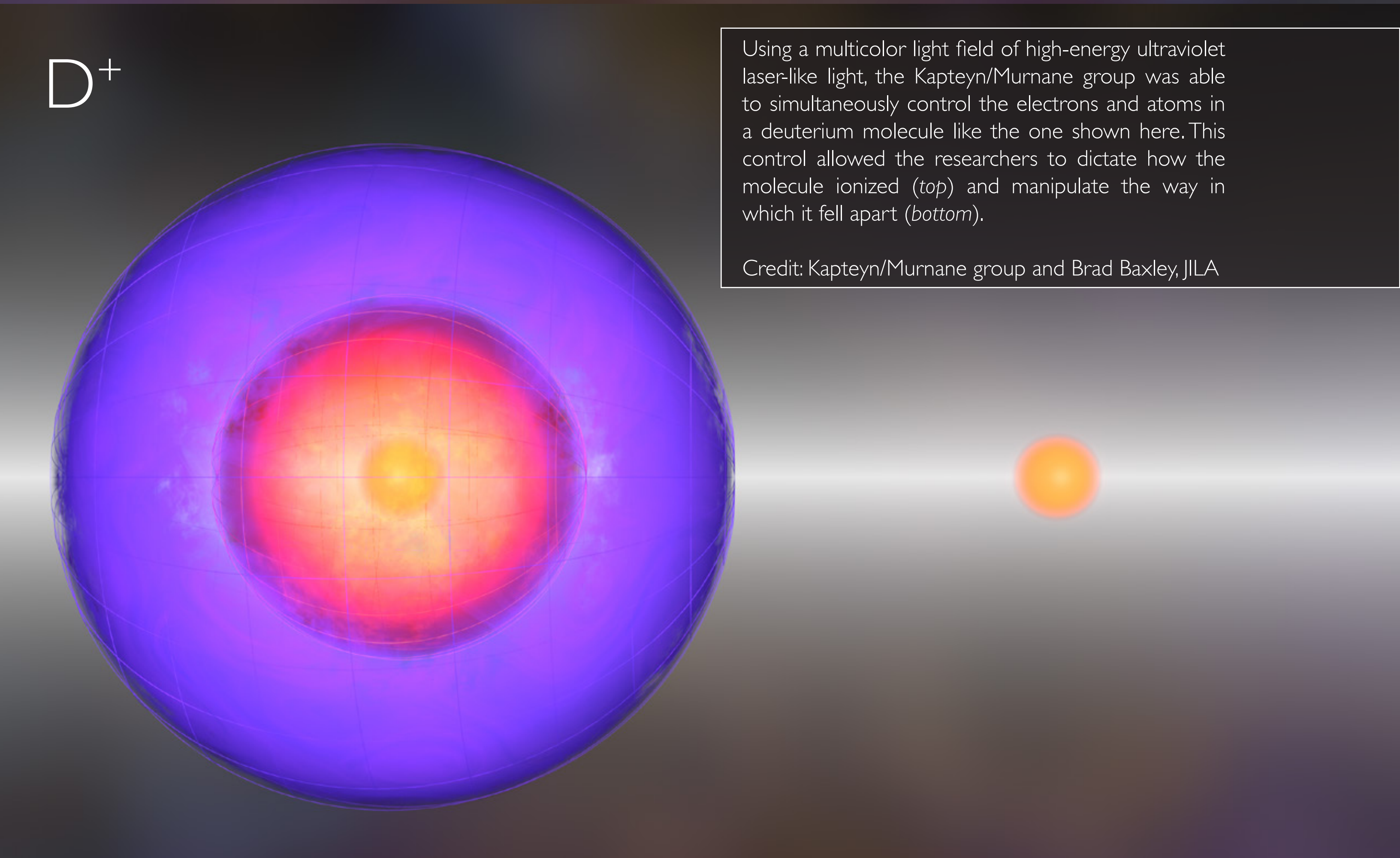
T. P. Purdy, P.-L. Yu, R. W. Peterson, N. S. Kampel, and C. A. Regal, *Physical Review X* **3**, 031012 (2013).



The Regal group uses a vibrating square drum (0.5mm on a side) inside an optical cavity to squeeze quantum noise out of the amplitude of laser light, allowing for more precise measurements. This "squeeze machine" sits inside a metal holder approximately one inch in diameter.

Photo credit: Brad Baxley, JILA





Using a multicolor light field of high-energy ultraviolet laser-like light, the Kapteyn/Murnane group was able to simultaneously control the electrons and atoms in a deuterium molecule like the one shown here. This control allowed the researchers to dictate how the molecule ionized (*top*) and manipulate the way in which it fell apart (*bottom*).

Credit: Kapteyn/Murnane group and Brad Baxley, JILA

MISSION: CONTROL

Capturing and controlling the fleeting dance of electrons as they rearrange during a chemical reaction has been a long-standing challenge in science for several decades. Since electrons are much lighter than atoms, they can respond almost instantaneously—on time scales of hundreds of attoseconds, where an attosecond is 10^{-18} s.

Fortunately, over the last decade scientists have created attosecond x-ray strobe lights that are fast enough to freeze the motion of electrons. However, simply illuminating a molecule with an attosecond flash of x-ray light would not work because one law of quantum mechanics dictates that an attosecond burst of light must span a broad energy range. Thus, scientists could not tell how the energy of an electron changes during a chemical reaction; nor could they use laser light to steer the outcome of a chemical reaction.

Fortunately, the Kapteyn/Murnane group has learned how to make a multicolor light field consisting of a series of finely tuned attosecond bursts of high-energy ultraviolet (UV) laser-like light of carefully selected wavelengths. Using this optimized light field, they were able to coax an electron to hop from one energy level to another on attosecond time scales. The researchers used this ability to simultaneously control both the electrons and atoms in a deuterium (D_2) molecule.

This exquisite control allowed them to dictate the exact pathway by which the molecule loses an electron (ionizes), regulate the way the molecule vibrates, and even manipulate the way in which the molecule falls apart. Figuring out how to use quantum physics to control chemical reactions even in a simple molecule like D_2 was both daunting and remarkable.

The researchers responsible for this important breakthrough include former research associate Predrag Ranitovic, graduate student Craig Hogle, former undergraduate student Leigh Martin, Fellows Margaret Murnane and Henry Kapteyn, as well as colleagues from the University of Tsukuba (Japan), Universidad Autónoma de Madrid (Spain), and Instituto Madrileño de Estudios Avanzados en Nanociencia (Spain).

The Kapteyn/Murnane group expects this breakthrough to lead to new and better ideas for using ultrafast lasers and x-ray pulses to control chemical reactions. — *Margaret Murnane and Julie Phillips*

Reference

Predrag Ranitovic, Craig W. Hogle, Paula Rivière, Alicia Palacios, Xiao-Ming Tong, Nobuyuki Toshima, Alberto González-Castrillo, Leigh Martín, Margaret M. Murnane, and Henry Kapteyn, *Proceedings of the National Academy of Sciences of the United States of America* **111**, 912–917 (2014).

THE GREAT SPIN SWAP

Research associate Bo Yan and his colleagues recently observed spin exchanges in ultracold potassium-rubidium (KRb) molecules inside an optical lattice (a crystal of light formed by interacting laser beams). In solid materials, such spin exchanges are the building blocks of advanced materials and exotic behaviors.

The spin exchanges occurred when a rotationally excited KRb molecule interacted with a non rotating KRb molecule in the ground state. Amazingly, the two molecules could be relatively far apart and confined in separate energy wells in the lattice, but still interact with one another. These interactions can result in the molecules swapping their quantum spin states! When this happens, the rotating molecule stops spinning and enters its ground state, while the second molecule starts spinning and becomes excited. Remarkably, all of the molecules stay in their original positions inside the lattice the entire experiment.

Yan's pioneering experiment was the first ever to "see" spin-exchange interactions in the laboratory (at the relatively "high" temperature of 200 nK). However, theorists had been predicting them for almost 10 years. Yan's fellow researchers included graduate students Steven Moses and Jake Covey, research associates Bryce Gadway and Kaden Hazzard, and Fellows Ana Maria Rey, Debbie Jin, and Jun Ye. Their work appeared in *Nature*.

To observe the great spin swap, the researchers had to overcome two key technical challenges. The first challenge was to "see" the spin swap in a noisy environment with lots of other things happening. The researchers solved this problem with a creative noise filter.

The second challenge was due to the sophisticated microwave control needed for the experiment and the interactions of the laser light creating the optical lattice confining the molecules. Unfortunately there was no "magic" wavelength of the laser light that could control the energies of the different spins in the same way. Fortunately, however, there was a "magic" angle. By changing the angle of the laser, the researchers were able to reduce the light-molecule interactions enough to detect long-lived quantum superpositions of the two possible molecular spin states in pairs of KRb molecules in the process of spin swapping.

The ability to observe spin swapping promises to impact future research in high-temperature superconductivity, energy transport through biomolecules and in chemical reactions, spintronics (a new kind of microelectronics), and the physics of liquids and solids. Because spin-exchange interactions are critical to understanding all these systems, their observation in the laboratory is a significant advance that will stimulate new physics research for years to come.

Reference

Bo Yan, Steven A. Moses, Bryce Gadway, Jacob P. Covey, Kaden R. A. Hazzard, Ana Maria Rey, Deborah S. Jin, and Jun Ye, *Nature* **501,** 521–525 (2013).

For the first time ever, the Jin-Ye collaboration has observed KRb molecules swapping spin states inside an optical lattice.

Credit: The Ye–Jin collaboration and Brad Baxley, JILA

A three-dimensional glowing sphere of stellar debris looks like a star when it envelops a small supermassive black hole.

Credit: The Begelman group and Brad Baxley, JILA

GUESS WHAT'S COMING TO DINNER

Black holes have a new item on their dinner menu: a three-dimensional glowing sphere of stellar debris that looks like a star. The sphere provides a sumptuous main course for a supermassive black hole, while emitting excess energy via jets erupting from its polar regions. The idea for this new type of gourmet feast for black holes comes compliments of graduate student Eric Coughlin and Fellow Mitch Begelman.

Of course, astrophysicists have known for a long time that supermassive black holes feed on stellar debris. Stars in orbit around these black holes are subject to powerful tidal forces that can steal their outer layers or even blow them apart. Until now, however, scientists thought this debris simply formed a disk around the black hole.

However, something else can happen with smaller monster black holes with a mass of ~ 1 million suns, according to Coughlin and Begelman. Material can flow into the black hole so rapidly that the black hole emits enough radiation to puff up the disk of stellar debris into a sphere.

But, soon the new sphere of hot gas has a problem: what to do about all the energy the black hole is liberating as it feasts on the stellar debris that surrounds it. This is an easy problem to solve when dinner is a disk: energy can rapidly dissipate in all sorts of directions.

However, there's no easy way out for all this energy in a glowing sphere of stardust. At first, the hot gas just absorbs the energy. But, eventually it has to spit out all this energy either by (1) blowing itself to bits, or, more often, (2) forming the jets that erupt from its poles sometime after the debris puffs up.

But, why do some disks puff up in the first place? Coughlin and Begelman think they have figured out the answer to that question, too. Even though a star had a lot of angular momentum as it spins in orbit around a black hole, it doesn't always have enough angular momentum to maintain a debris disk around a black hole after the star is destroyed. When this happens, the debris puffs up and looks like a star.

Coughlin and Begelman are now investigating whether their new understanding of the behavior of tidal debris around black holes will shed light on what happens to generate short and long gamma ray bursts during the collapse of stars into neutron stars or stellar-sized black holes.

Reference

Eric R. Coughlin and Mitchell C. Begelman, *Astrophysical Journal* **781**, 82 (2014).

KUDOS TO…

Eric Cornell for his featured role in NOVA's "Making Stuff Colder" show, which aired on October 30, 2013.

Steve Cundiff for being named an IEEE Fellow "for contributions to self-referenced optical frequency combs and ultrafast nonlinear solid-state spectroscopy." This honor is bestowed on only about one tenth of one percent of IEEE members.

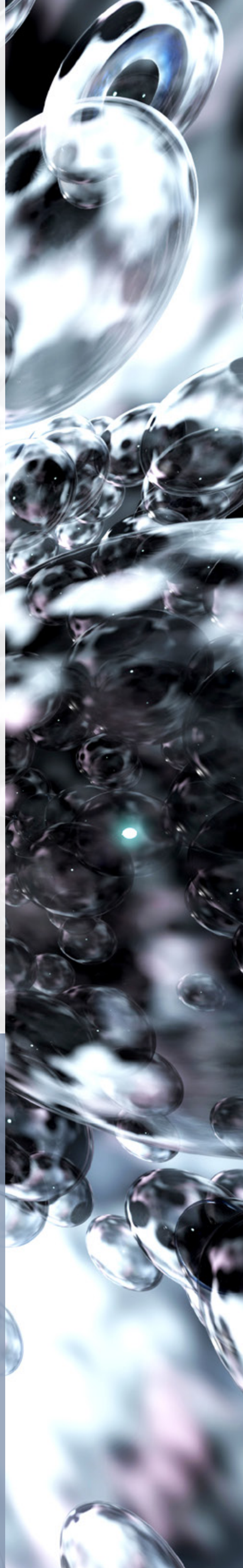
Deborah Jin for being awarded the 2014 Comstock Prize in Physics by the National Academy of Sciences. She was cited for "demonstrating quantum degeneracy and the formation of a molecular Bose-Einstein condensate in ultracold fermionic atoms gases, and for pioneering work in polar molecular quantum chemistry."

Konrad Lehnert for being named a Fellow of the American Physical Society. He was cited "for developing experimental methods that enable the quantum control and measurement of micro-mechanical oscillators and for developing practical microwave amplifiers that operate at the quantum limit."

Markus Raschke for being named a 2013 Fellow of the American Physical Society. He was cited for his contributions to surface and near-field optics involving nanospectroscopy, optical control, thermal near-field spectroscopy, optical nanoantennas and adiabatic nanofocusing in nonlinear and ultrafast nanoimaging.

Ana Maria Rey for being selected to receive a 2013 Presidential Early Career Aaward for Scientists and Engineers. The award is the highest honor bestowed by the United States government on science and engineering professionals in the early stages of their careers.

CG artist **Brad Baxley** for winning first prize in the Jennie Smoly Caruthers Biotechnology-Building Art Competition. His winning photograph Pervasion captured the intricate single neutral atom-trapping apparatus in the Cindy Regal lab.



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